EEC2146: Electronic Circuits and Measurements

Prepared by:
Dr. Hossam Kasem

Email:
hossam.kasem@f-eng.tanta.eg
hossamkasem1@gmail.com

EEC2146: Electronic Circuits and Measurements

LEC: 3
Amplifier Frequency Response

Amplifier Frequency Response

Objectives and outline:

- Explain how circuit capacitances affect the frequency response of an amplifier
- Use the decibel (dB) to express amplifier gain
- Analyze the low-frequency response of an amplifier
- Analyze the high-frequency response of an amplifier
- Analyze an amplifier for total frequency response
- Analyze multistage amplifiers for frequency response
- Measure the frequency response of an amplifier

Amplifier Frequency Response

Introduction and Definition

- In this chapter, we study the effect of operating frequency on the voltage gain of the BJT and MOST amplifiers.
- In determining the voltage gain in the previous chapter, we assumed that the gain of the amplifier was independent of the input signal frequency.
- However, BJT and FET have small internal capacitances due to their physical structure. ***As a result of these capacitances the gain of the BJT and FET are frequency dependent and decrease with the increasing of the input signal frequency***. The internal capacitances set the upper frequency limit of transistors amplifiers.

Amplifier Frequency Response

Introduction and Definition

- Practical amplifiers are often connected to the input signal source and the load resistance through large external capacitances (called coupling capacitances) which effectively block the low frequency signal. External capacitances are also employed to effectively bypass resistors in order to increase the small signal voltage gain(these capacitances are called bypassing capacitors).
- **Thus the performance of the amplifiers depends on the input signal frequency, and the design specification usually quotes the voltage gain at specified frequency range known as the Bandwidth.**

Amplifier Frequency Response

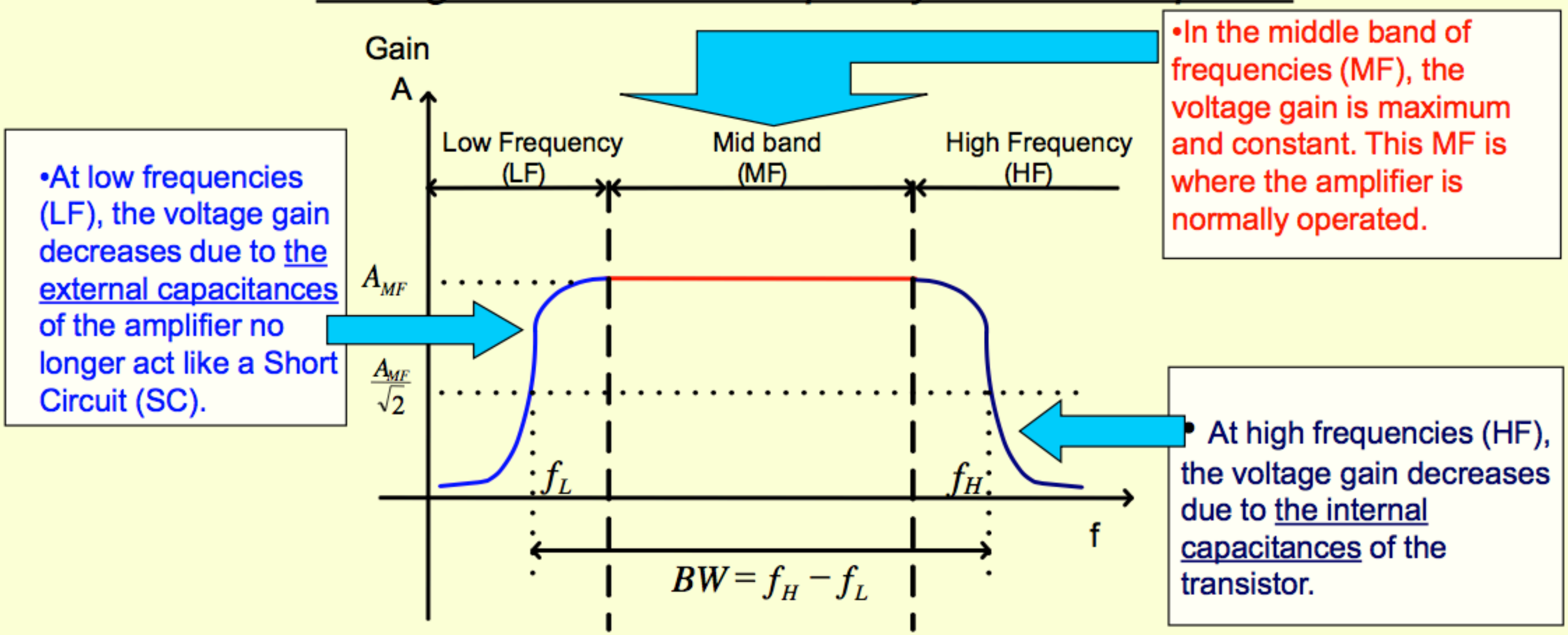
1-Amplifier Frequency Response

- *The frequency response of an amplifier is the graph of its gain versus the frequency*

Amplifier Frequency Response

1- Amplifier Frequency Response

The figure shows the frequency of an ac amplifier:



Amplifier Frequency Response

(2) External Capacitances (μ F)

(i) Coupling Capacitances

are used to decouple ac and dc signals so as not to disturb the quiescent point of the circuit when ac signals are injected at the input.

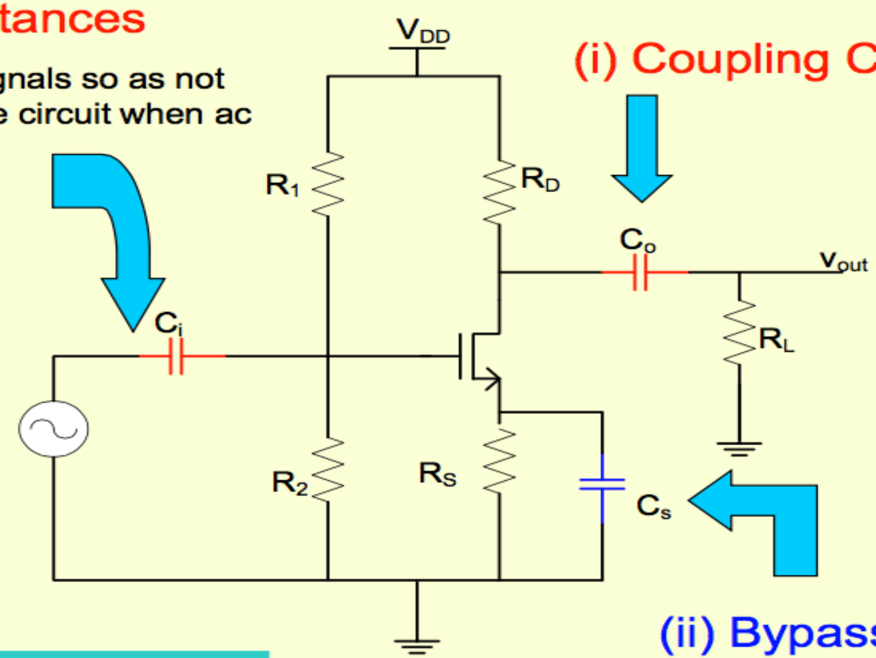
Typically, the external capacitors are large (in order of Micro Farad)

$$Z_C = \frac{1}{j\omega \, C_{external}}$$

In HF
capacitors act like a (SC)

In LF
capacitors are not act like a (SC)

(i) Coupling Capacitances



(ii) Bypassing capacitors

are used to force signal currents around elements by providing a low impedance path at the frequency.

Amplifier Frequency Response

(3) Internal Capacitances (pF):

(i) Coupling Capacitances

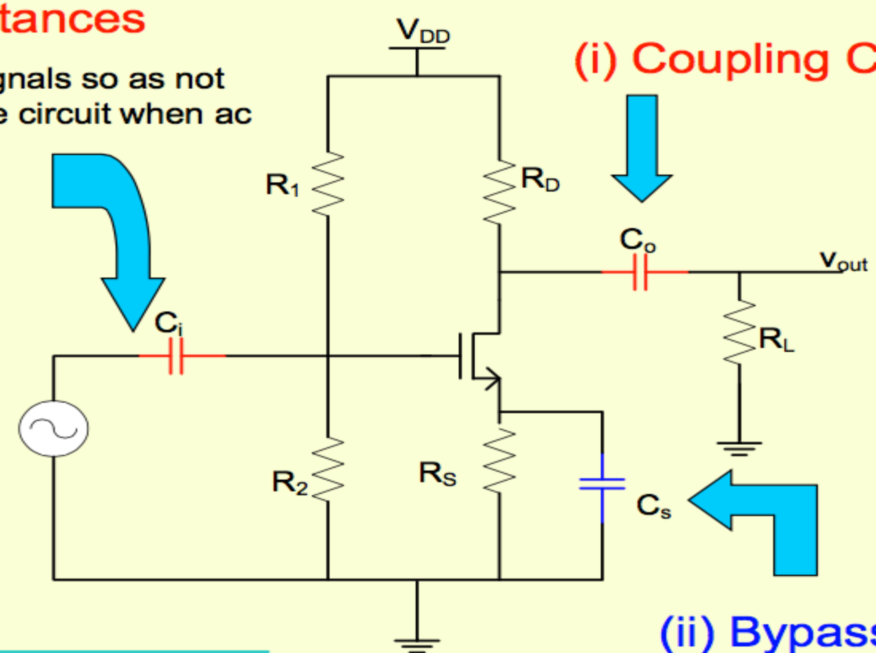
are used to decouple ac and dc signals so as not to disturb the quiescent point of the circuit when ac signals are injected at the input.

Typically, the external capacitors are large (in order of Micro Farad)

$$Z_C = \frac{1}{j\omega\, C_{external}}$$

In HF
capacitors act like a (SC)

In LF
capacitors are not act like a (SC)



(i) Coupling Capacitances

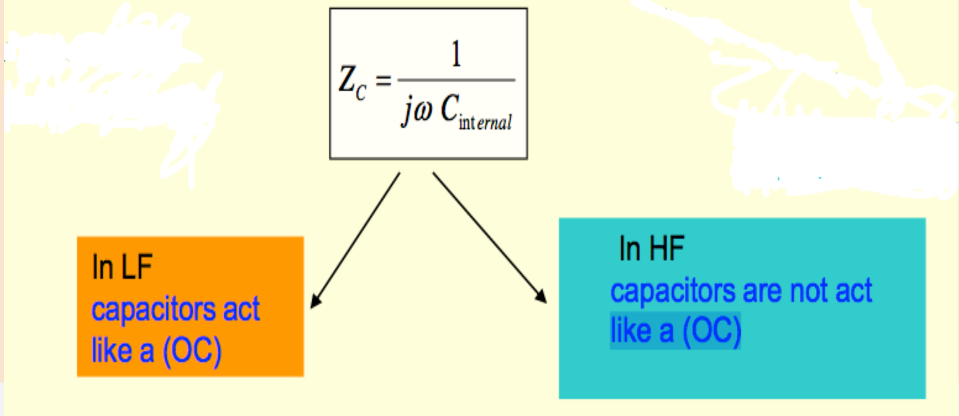
(ii) Bypassing capacitors

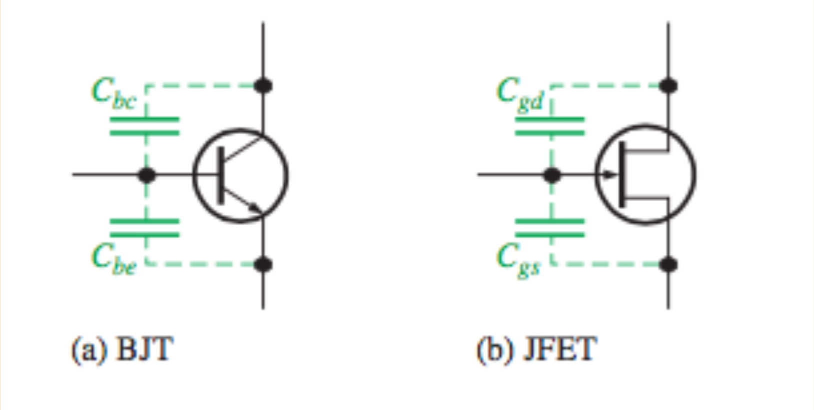
are used to force signal currents around elements by providing a low impedance path at the frequency.

Amplifier Frequency Response

(3) Internal Capacitances (pF):

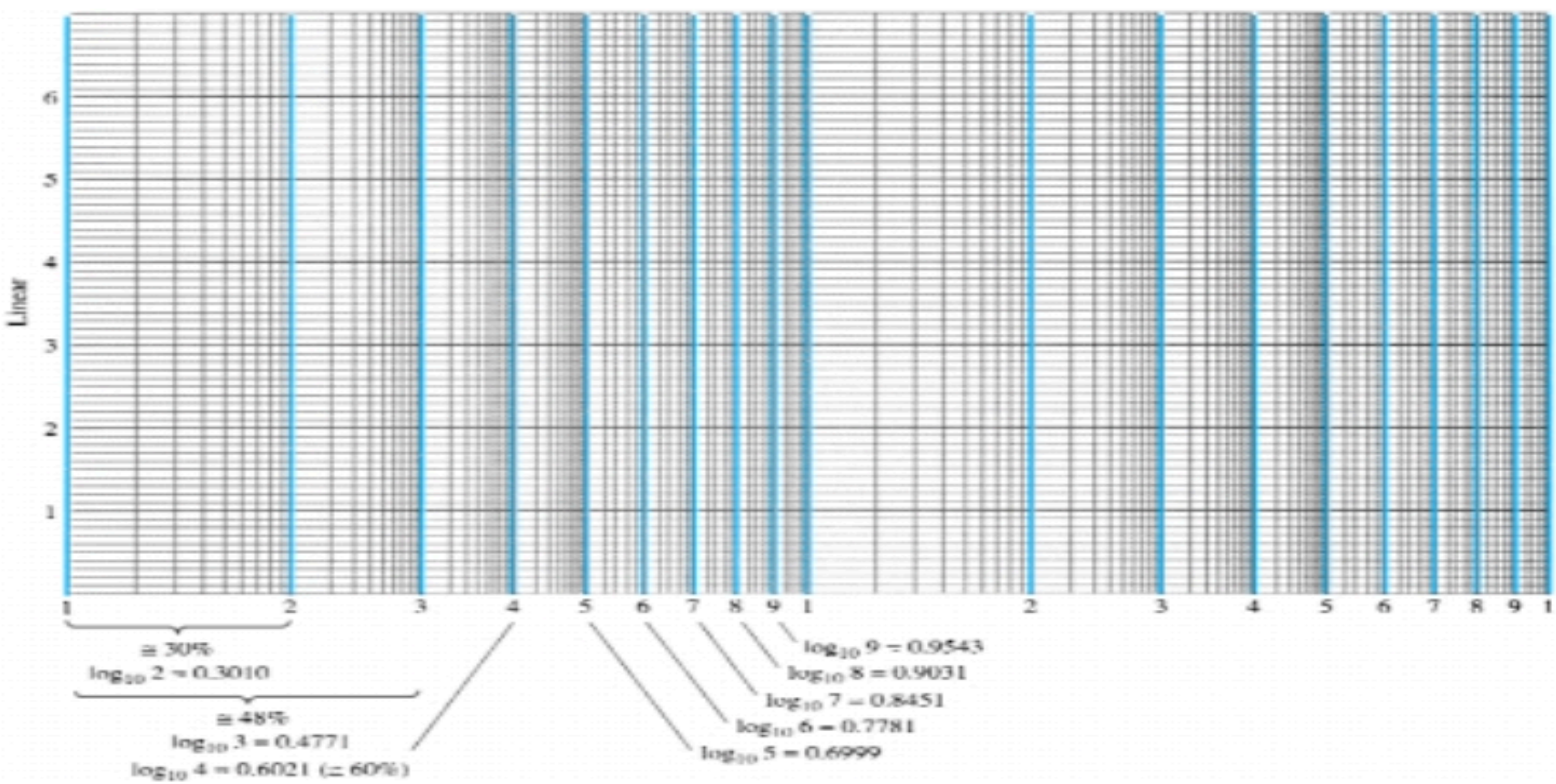
- At high frequencies, the coupling and bypass capacitors become effective ac shorts and do not affect an amplifier's response .
- Internal transistor junction capacitances, however, do come into play, reducing an amplifier's gain and introducing phase shift as the signal frequency increases.





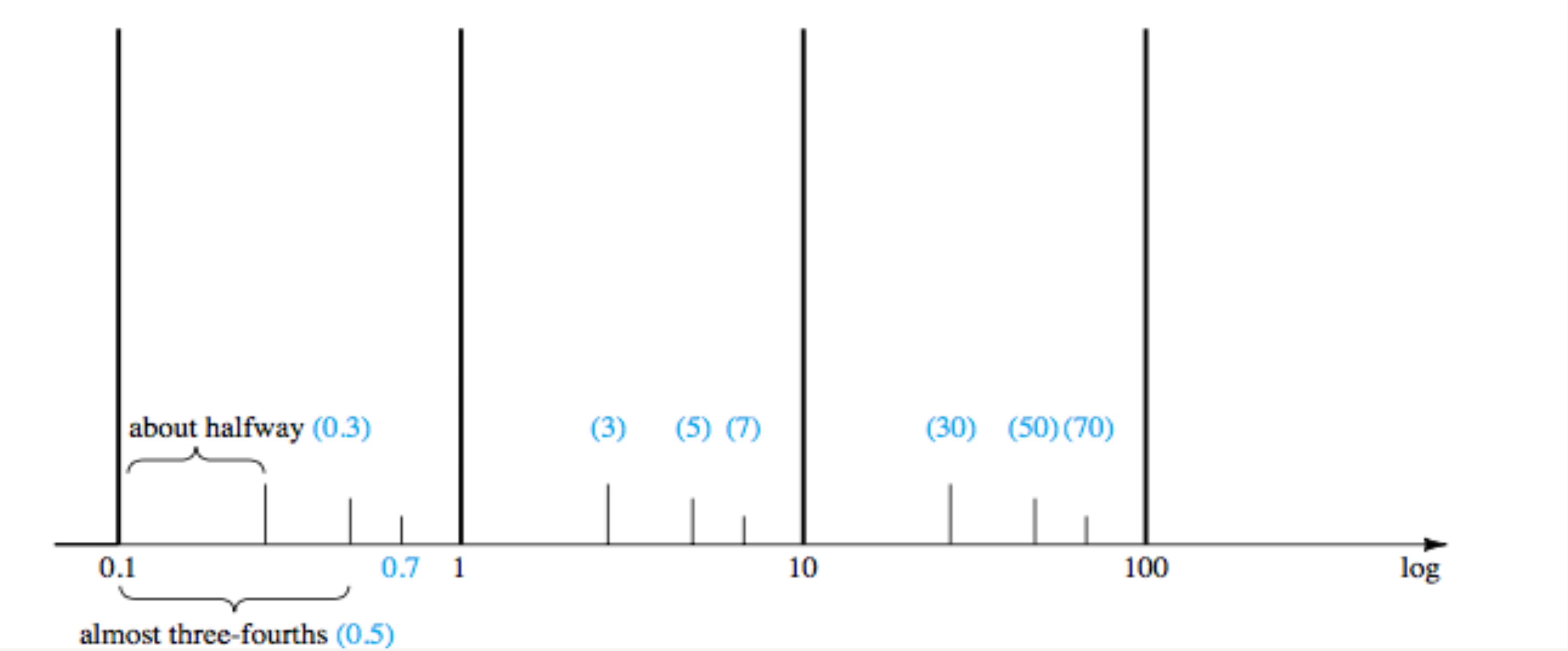
Amplifier Frequency Response

(4) Semilog graph paper:



Amplifier Frequency Response

(4) Semilog graph paper:



Amplifier Frequency Response

5- DECIBELS :

- The background surrounding the term *decibel* has its origin in the established fact that power and audio levels are related on a logarithmic basis.
- The bel (B) was defined by the following equation to relate power levels *P*1 and *P*2

$$\boxed{G = \log_{10}\frac{P_2}{P_1}} \quad \text{bel}$$

- the decibel (dB) was defined such that 10 decibels 1 bel.

$$\boxed{G_{\text{dB}} = 10\log_{10}\frac{P_2}{P_1}} \quad \text{dB}$$

Dr.Hossam kasem
Electronics and Electrical Comm. Dept.

Amplifier Frequency Response

5- DECIBELS :

- When the 1-mW level is employed as the reference level, the decibel symbol frequently appears as dBm. In equation form.

$$\boxed{G_{dBm} = 10 \log_{10} \frac{P_2}{1\text{ mW}}\bigg|_{600\ \Omega}} \qquad \text{dBm}$$

- The Voltage Gain can be expressed in term of dB as Follow:

$$G_{dB} = 10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{V_2^2/R_i}{V_1^2/R_i} = 10 \log_{10}\left(\frac{V_2}{V_1}\right)^2$$

$$\boxed{G_{dB} = 20 \log_{10} \frac{V_2}{V_1}} \qquad \text{dB}$$

Amplifier Frequency Response

5- DECIBELS :

- One of the advantages of the logarithmic relationship is the manner in which it can be applied to cascaded stages .

$$|A_{v_T}| = |A_{v_1}||A_{v_2}||A_{v_3}|\cdots|A_{v_n}|$$

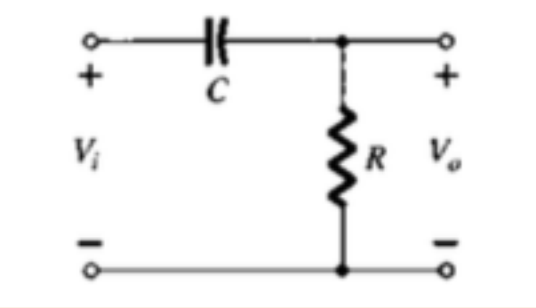
$$G_v = 20\log_{10}|A_{v_T}| = 20\log_{10}|A_{v_1}| + 20\log_{10}|A_{v_2}| + 20\log_{10}|A_{v_3}| + \cdots + 20\log_{10}|A_{v_n}| \quad \text{(dB)}$$

$$\boxed{G_v = G_{v_1} + G_{v_2} + G_{v_3} + \cdots + G_{v_n}} \quad \text{dB}$$

Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS— BODE PLOT:

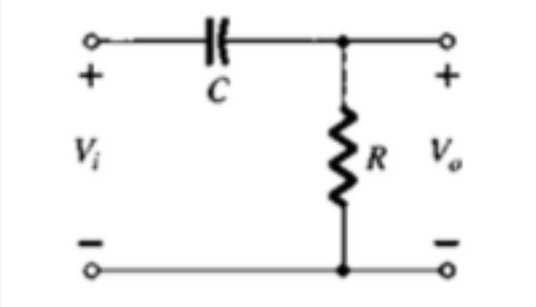
- In the low-frequency region of the single-stage BJT or FET amplifier, it is the *R*-*C* combinations formed by the network capacitors C_C, C_E, and C_s and the network resistive parameters that determine the cutoff frequencies.

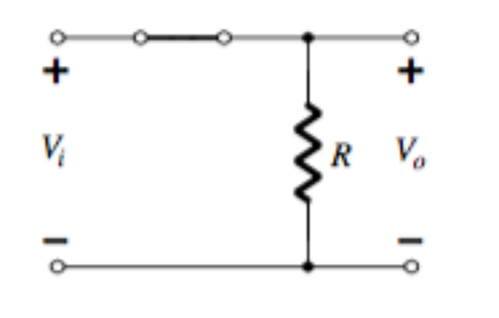


Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:

- At High frequency: $X_C = \dfrac{1}{2\pi f C} \cong 0\ \Omega$



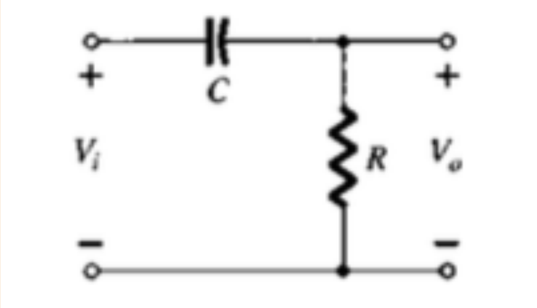


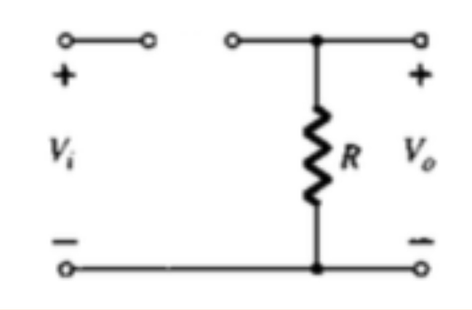
Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:

- At f=0 Hz:

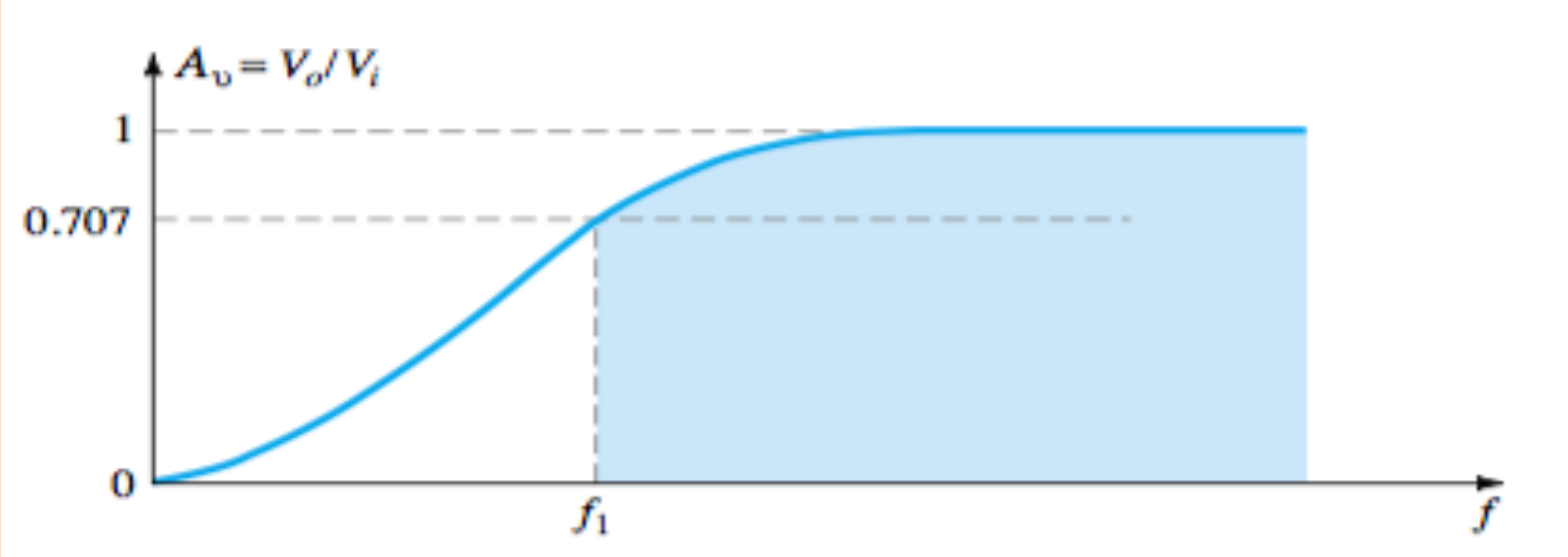
$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(0)C} = \infty\ \Omega$$





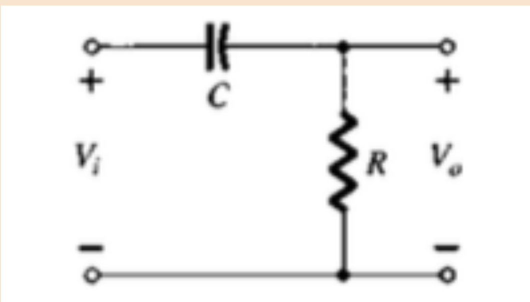
Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:



Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:



$$\mathbf{V_o = \frac{RV_i}{R + X_C}}$$

$$V_o = \frac{RV_i}{\sqrt{R^2 + X_C^2}}$$

For the special case where $X_C = R$,

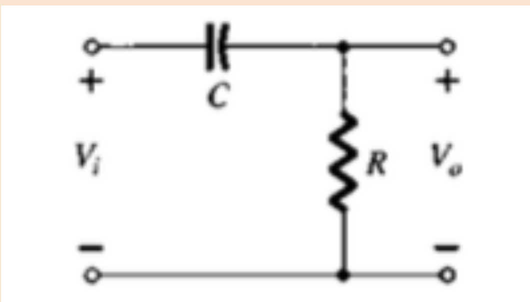
$$V_o = \frac{RV_i}{\sqrt{R^2 X_C^2}} = \frac{RV_i}{\qquad} = \frac{RV_i}{\sqrt{2R^2}} = \frac{RV_i}{\sqrt{2}R} = \frac{1}{\sqrt{2}} V_i$$

and

$$\boxed{|A_v| = \frac{V_o}{V_i} = \frac{1}{\sqrt{2}} = 0.707|_{X_C=R}}$$

Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:



$$X_C = \frac{1}{2\pi f_1 C} = R$$

and

$$\boxed{f_1 = \frac{1}{2\pi RC}}$$

$$G_v = 20 \log_{10} A_v = 20 \log_{10} \frac{1}{\sqrt{2}} = -3 \text{ dB}$$

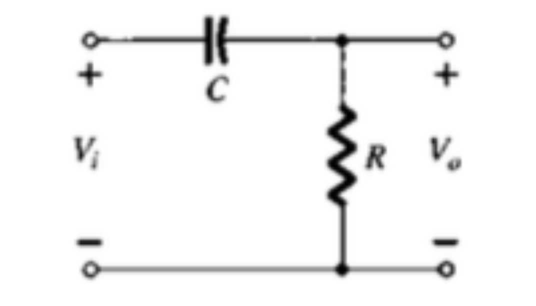
$$G_v = 20 \log_{10} 1 = 20(0) = 0 \text{ dB}$$

- General Voltage Gain :

$$A_v = \frac{V_o}{V_i} = \frac{R}{R - jX_C} = \frac{1}{1 - j(X_C/R)} = \frac{1}{1 - j(1/\omega CR)} = \frac{1}{1 - j(1/2\pi fCR)}$$

Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:



$$A_v = \frac{1}{1 - j(f_1/f)}$$

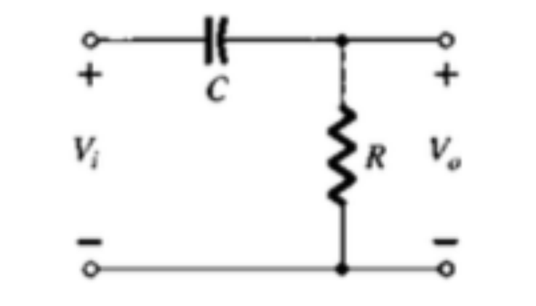
$$A_v = \frac{V_o}{V_i} = \underbrace{\frac{1}{\sqrt{1 + (f_1/f)^2}}}_{\text{magnitude of } A_v} \underbrace{\angle \tan^{-1}(f_1/f)}_{\text{phase} \measuredangle \text{ by which } V_o \text{ leads } V_i}$$

For the magnitude when $f = f_1$,

$$|A_v| = \frac{1}{\sqrt{1 + (1)^2}} = \frac{1}{\sqrt{2}} = 0.707 \rightarrow -3 \text{ dB}$$

Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:



$$A_{v(\mathrm{dB})} = 20 \log_{10} \frac{1}{\sqrt{1 + (f_1/f)^2}} = -20 \log_{10}\left[1 + \left(\frac{f_1}{f}\right)^2\right]^{1/2}$$

$$= -(\tfrac{1}{2})(20) \log_{10}\left[1 + \left(\frac{f_1}{f}\right)^2\right]$$

$$= -10 \log_{10}\left[1 + \left(\frac{f_1}{f}\right)^2\right]$$

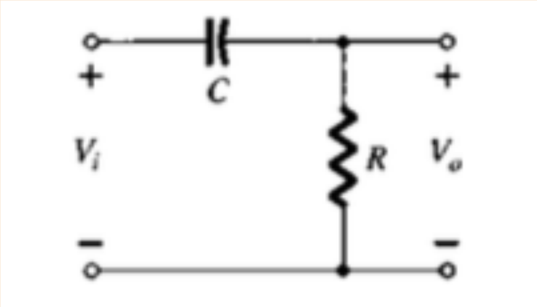
For frequencies where $f \ll f_1$ or $(f_1/f)^2 \gg 1$, the equation above can be approximated by

$$A_{v(\mathrm{dB})} = -10 \log_{10}\left(\frac{f_1}{f}\right)^2$$

$$\boxed{A_{v(\mathrm{dB})} = -20 \log_{10} \frac{f_1}{f}}_{f \ll f_1}$$

Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:



$$\text{At } f = f_1: \ \frac{f_1}{f} = 1 \text{ and } -20\log_{10} 1 = 0 \text{ dB}$$

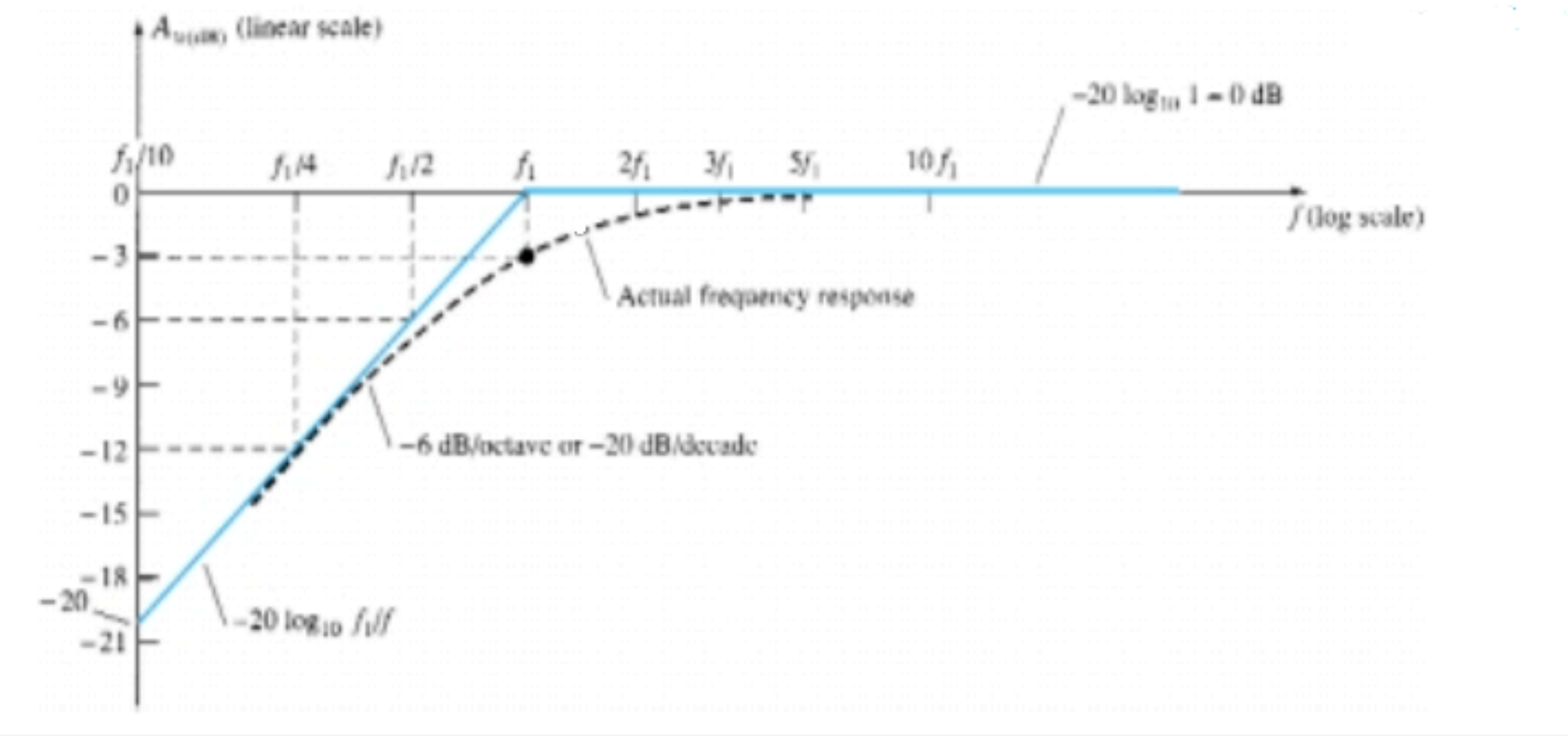
$$\text{At } f = \tfrac{1}{2} f_1: \ \frac{f_1}{f} = 2 \text{ and } -20\log_{10} 2 \cong -6 \text{ dB}$$

$$\text{At } f = \tfrac{1}{4} f_1: \ \frac{f_1}{f} = 4 \text{ and } -20\log_{10} 4 \cong -12 \text{ dB}$$

$$\text{At } f = \tfrac{1}{10} f_1: \ \frac{f_1}{f} = 10 \text{ and } -20\log_{10} 10 = -20 \text{ dB}$$

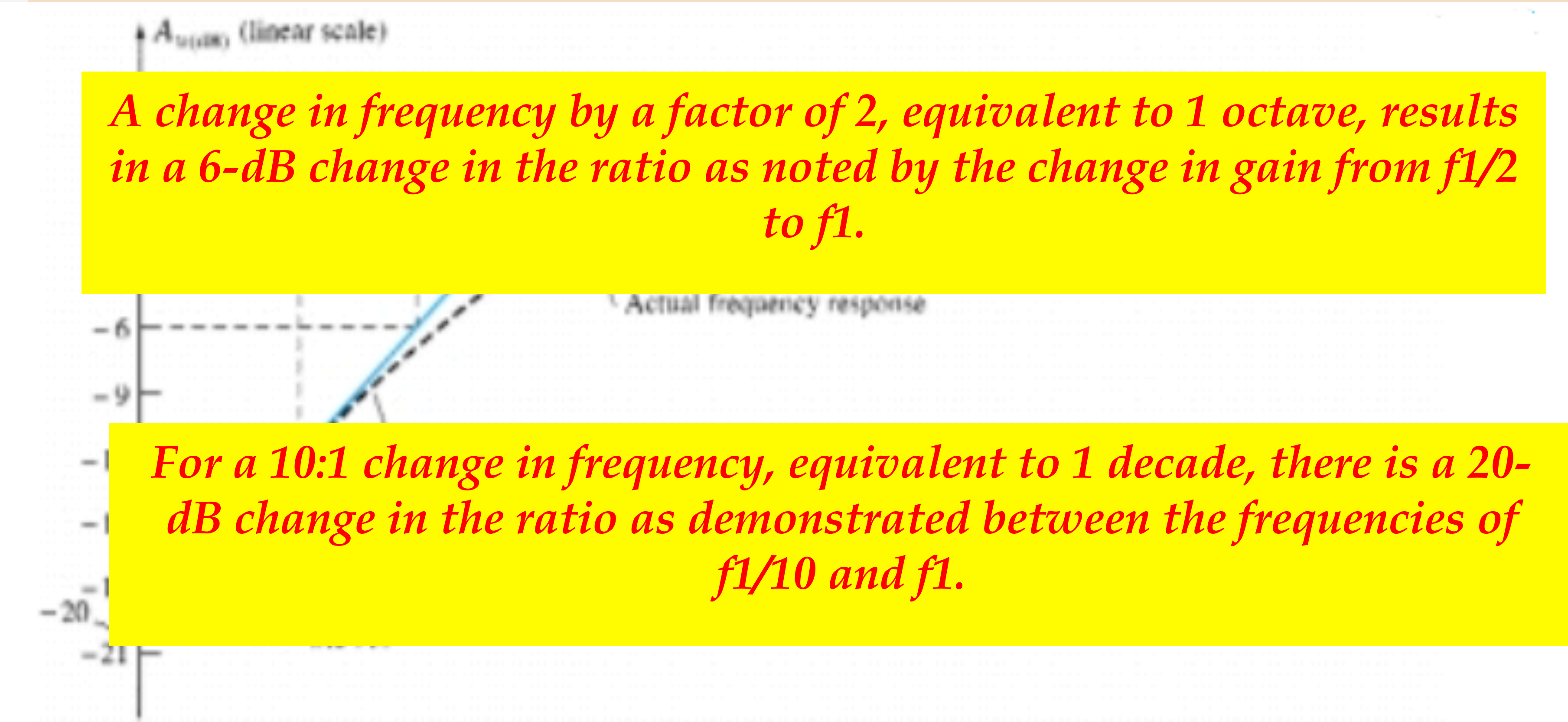
Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS – BODE PLOT:



Amplifier Frequency Response

LOW-FREQUENCY ANALYSIS— BODE PLOT:

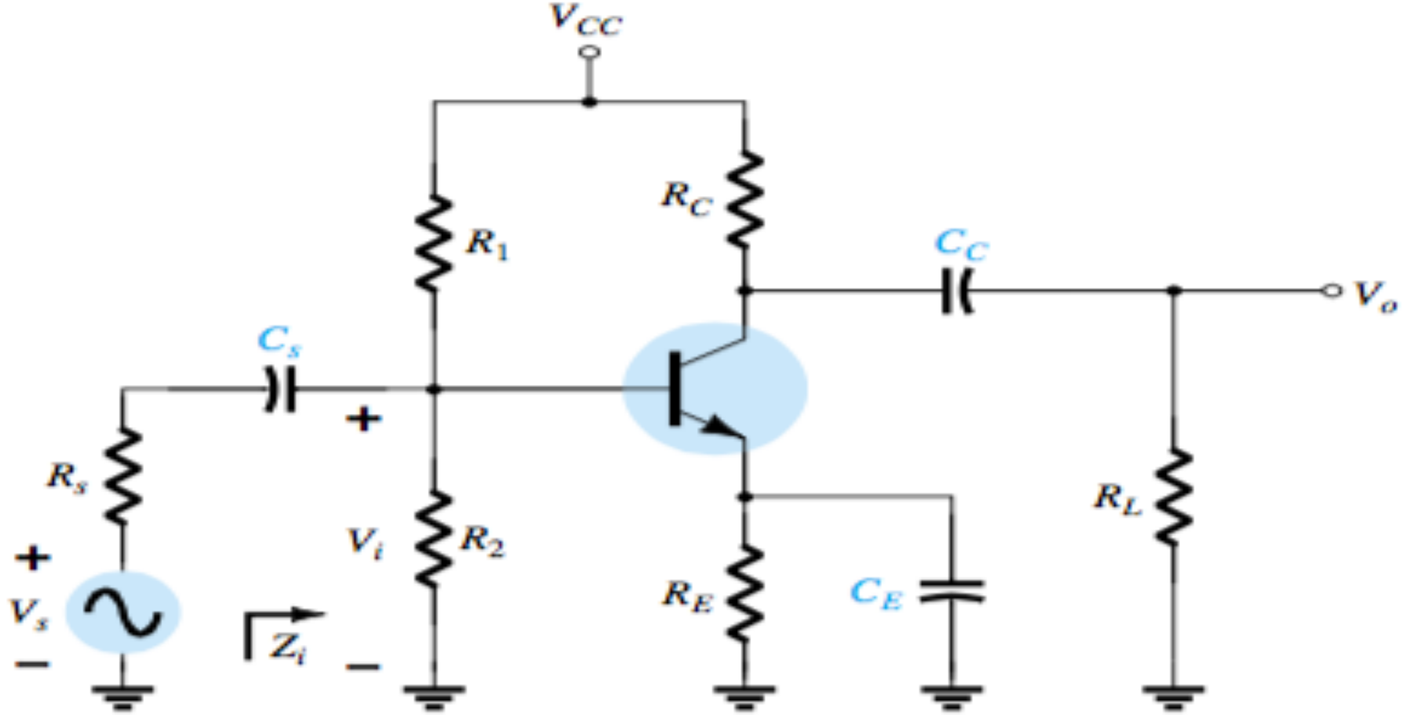


A change in frequency by a factor of 2, equivalent to 1 octave, results in a 6-dB change in the ratio as noted by the change in gain from f1/2 to f1.

For a 10:1 change in frequency, equivalent to 1 decade, there is a 20-dB change in the ratio as demonstrated between the frequencies of f1/10 and f1.

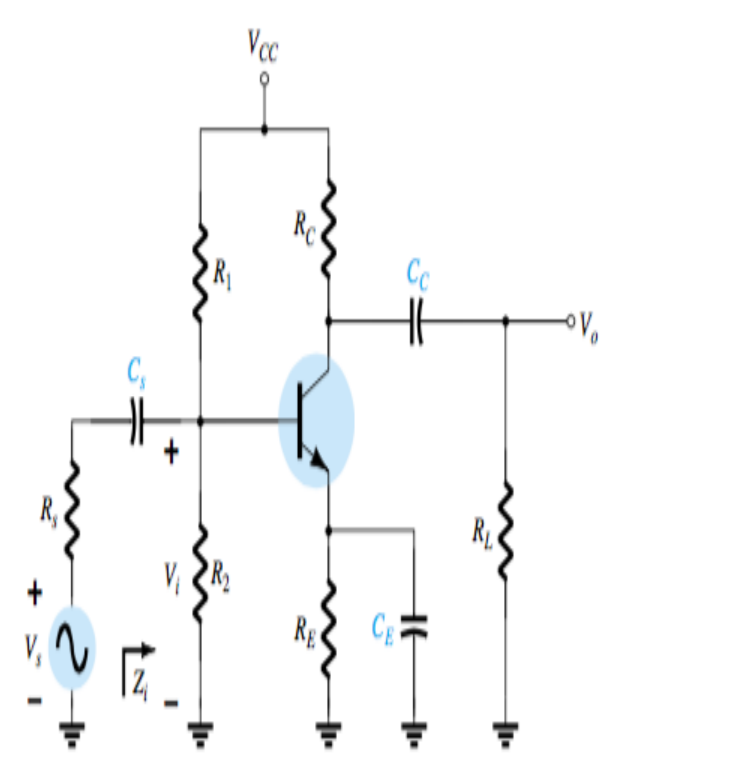
Amplifier Frequency Response

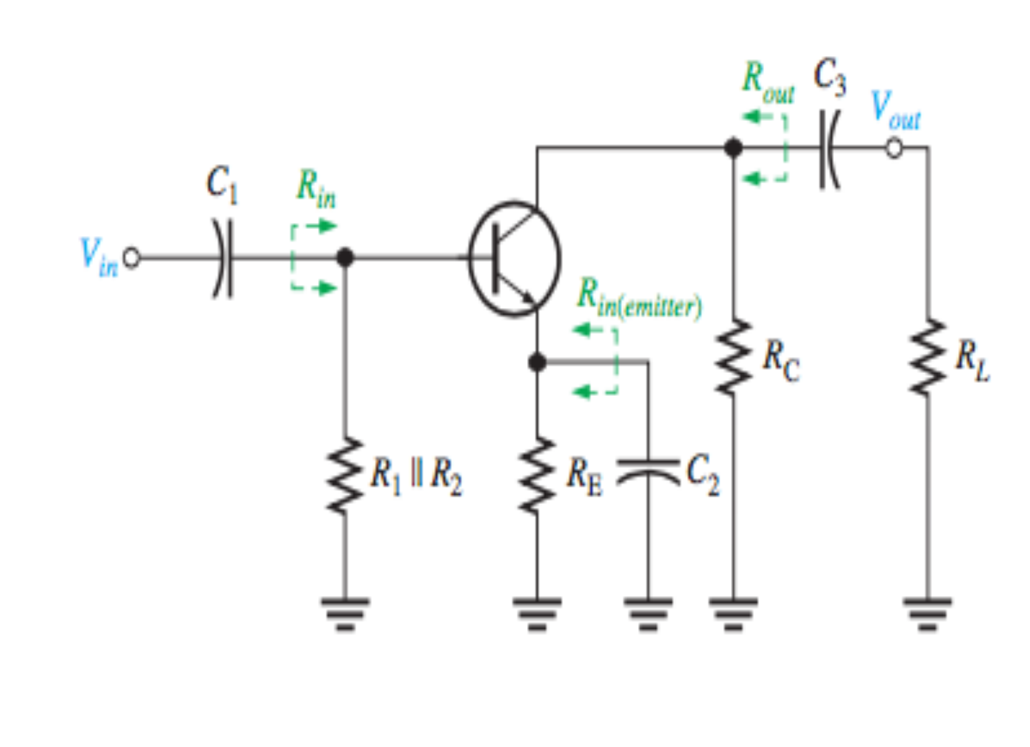
LOW-FREQUENCY RESPONSE – BJT AMPLIFIER



Amplifier Frequency Response

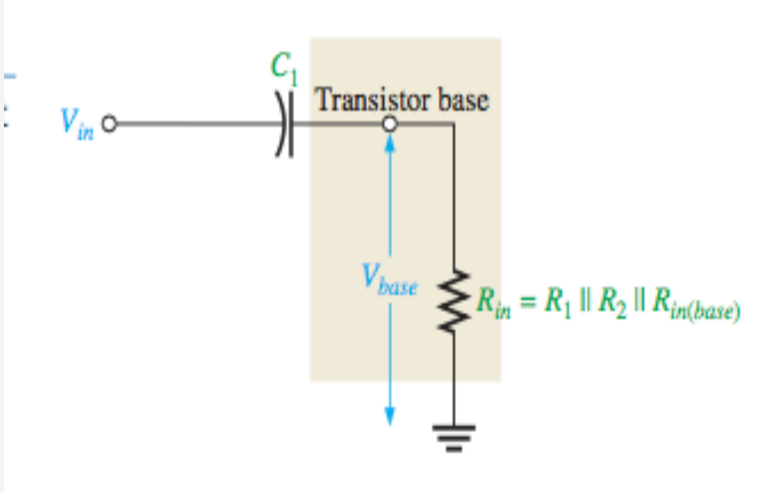
LOW-FREQUENCY RESPONSE – BJT AMPLIFIER





Amplifier Frequency Response

The Input *RC* Circuit



$$V_{base} = \left(\frac{R_{in}}{\sqrt{R_{in}^2 + X_{C1}^2}}\right)V_{in}$$

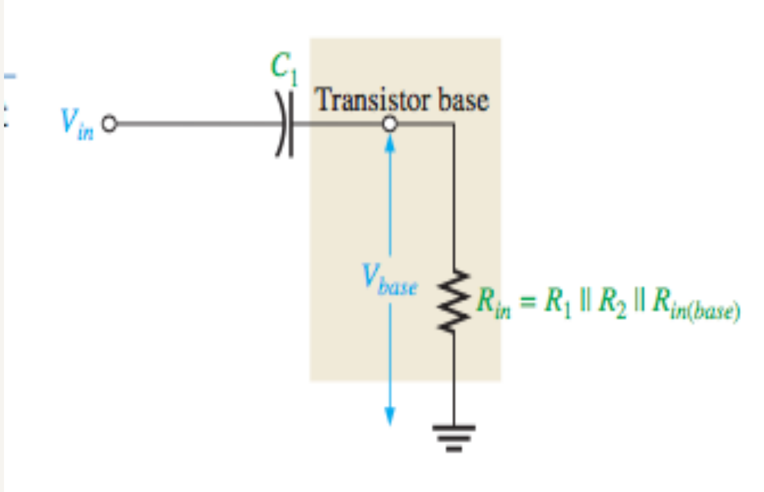
If R=X$_{C1}$

$$V_{base} = \left(\frac{R_{in}}{\sqrt{R_{in}^2 + R_{in}^2}}\right)V_{in} = \left(\frac{R_{in}}{\sqrt{2R_{in}^2}}\right)V_{in} = \left(\frac{R_{in}}{\sqrt{2}R_{in}}\right)V_{in} = \left(\frac{1}{\sqrt{2}}\right)V_{in} = 0.707V_{in}$$

$$20 \log \left(\frac{V_{base}}{V_{in}}\right) = 20 \log (0.707) = -3 \text{ dB}$$

Amplifier Frequency Response

The Input *RC* Circuit



Lower Critical Frequency

$$X_{C1} = \frac{1}{2\pi f_{cl(input)} C_1} = R_{in}$$

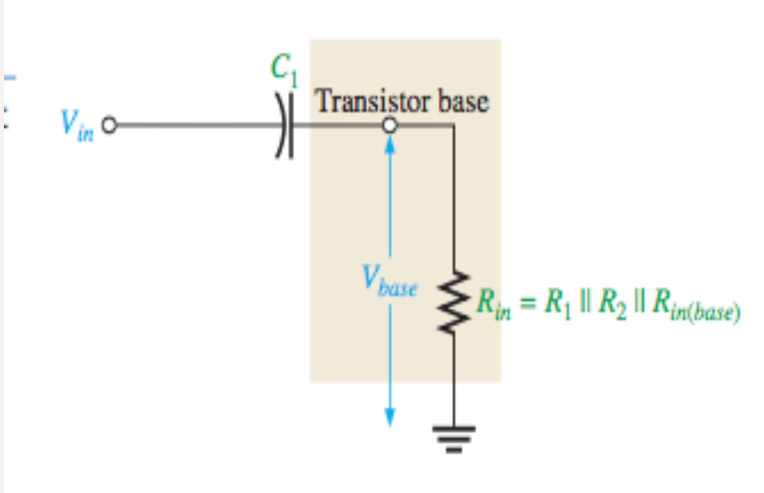
$$f_{cl(input)} = \frac{1}{2\pi R_{in} C_1}$$

If the resistance of the input source is taken into account,

$$f_{cl(input)} = \frac{1}{2\pi (R_s + R_{in}) C_1}$$

Amplifier Frequency Response

The Input *RC* Circuit



Phase Shift in the Input RC Circuit

$$\theta = \tan^{-1}\left(\frac{X_{C1}}{R_{in}}\right)$$

For midrange frequencies, $X_{C1} \cong 0\ \Omega$, so

$$\theta = \tan^{-1}\left(\frac{0\ \Omega}{R_{in}}\right) = \tan^{-1}(0) = 0°$$

At the critical frequency, $X_{C1} = R_{in}$, so

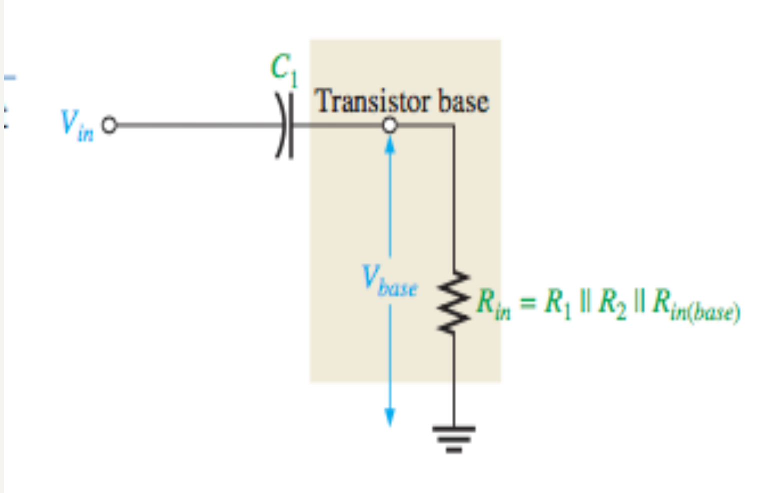
$$\theta = \tan^{-1}\left(\frac{R_{in}}{R_{in}}\right) = \tan^{-1}(1) = 45°$$

At a decade below the critical frequency, $X_{C1} = 10R_{in}$, so

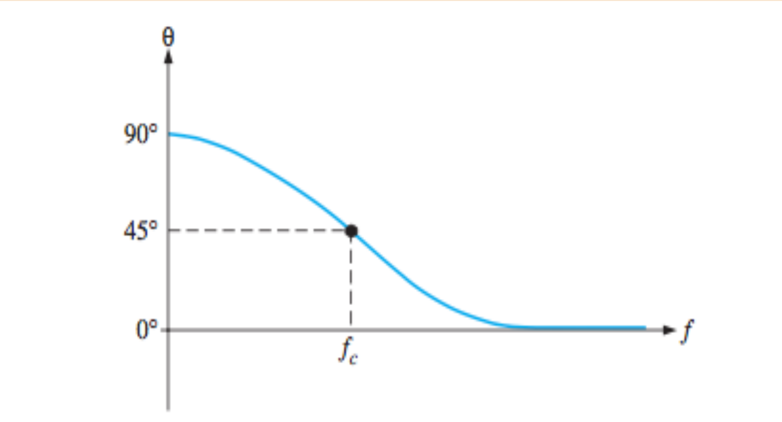
$$\theta = \tan^{-1}\left(\frac{10R_{in}}{R_{in}}\right) = \tan^{-1}(10) = 84.3°$$

Amplifier Frequency Response

The Input *RC* Circuit

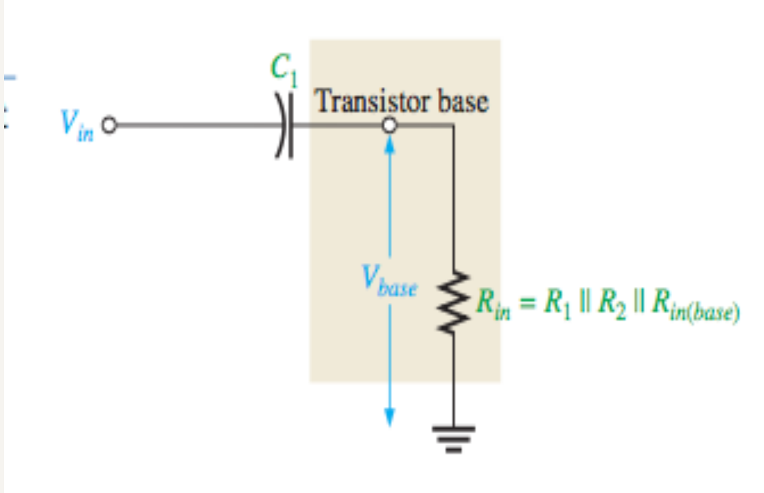


Phase Shift in the Input RC Circuit

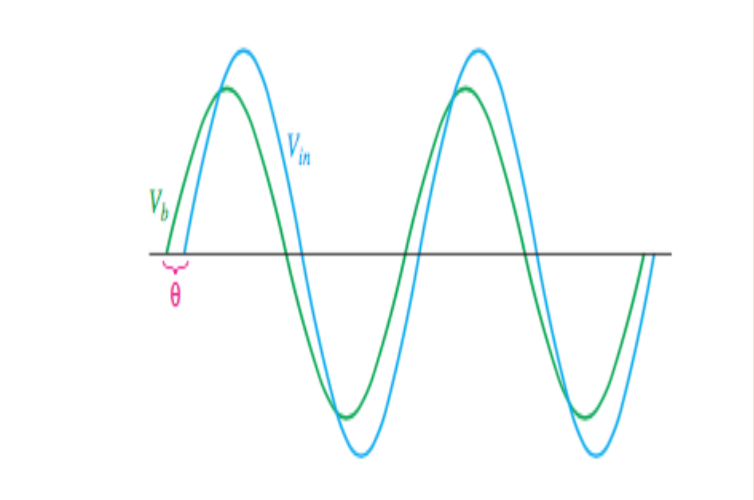


Amplifier Frequency Response

The Input *RC* Circuit

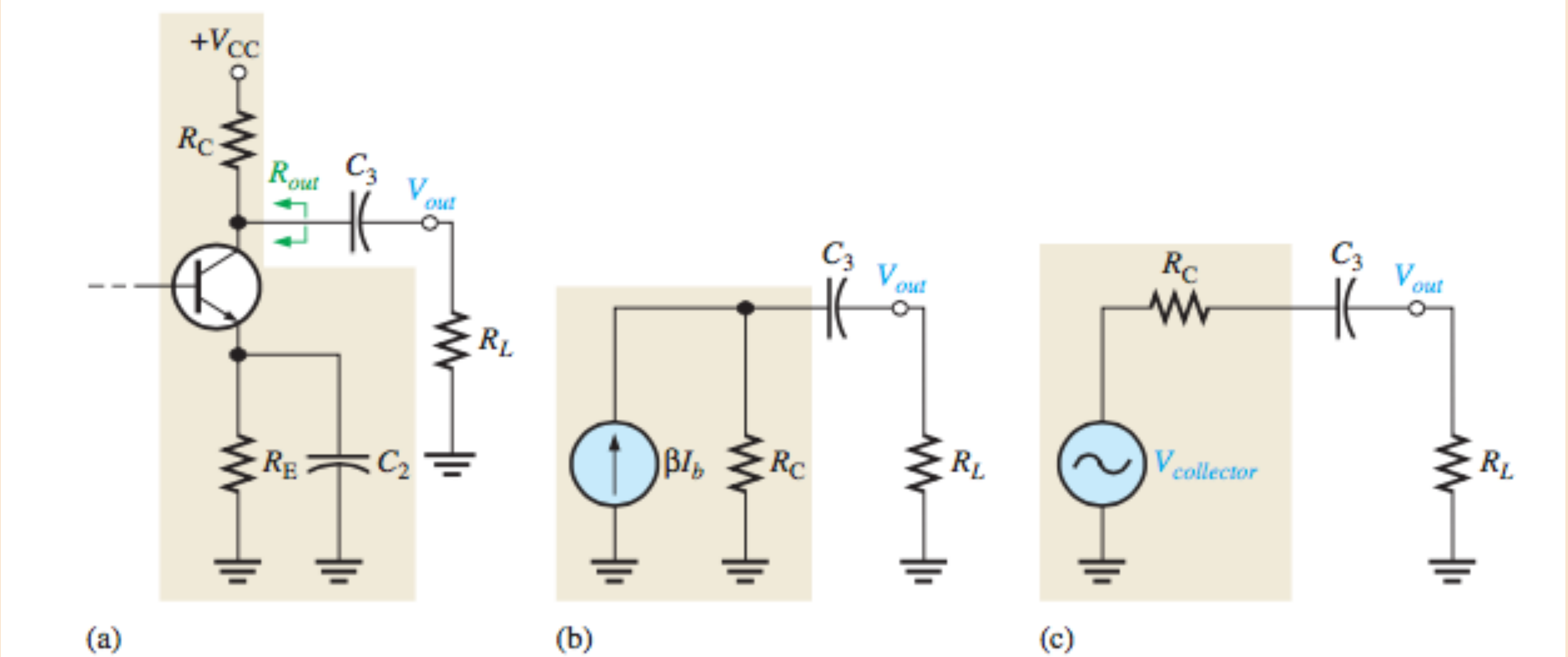


Phase Shift in the Input RC Circuit



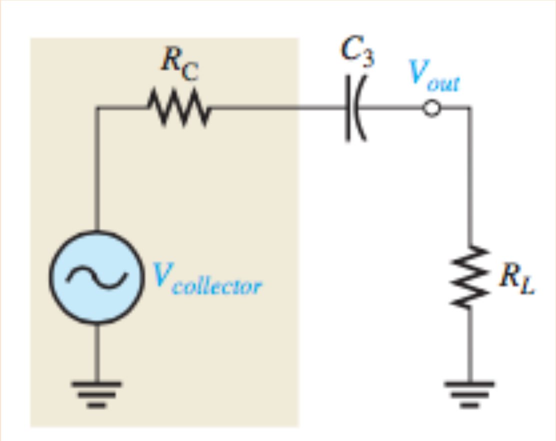
Amplifier Frequency Response

The Output *RC* Circuit



Amplifier Frequency Response

The Output *RC* Circuit



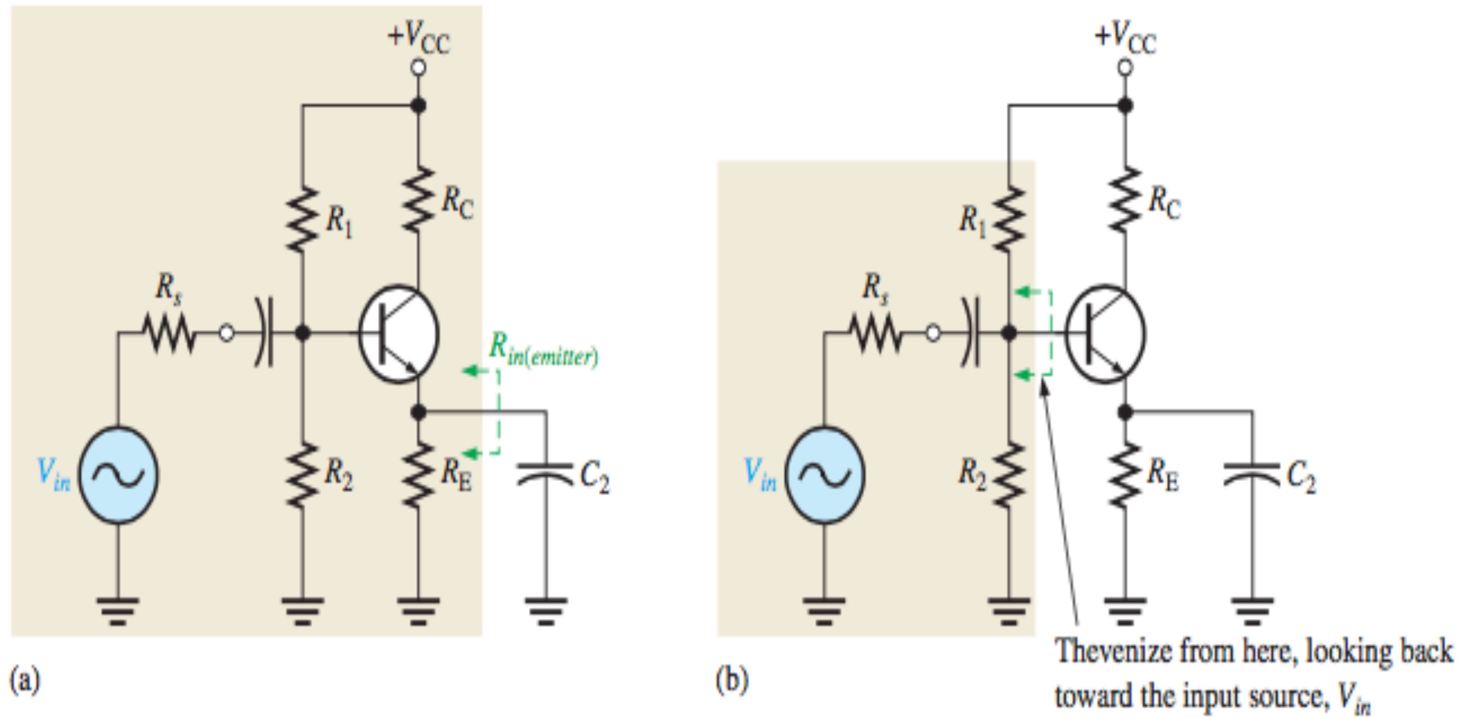
$$f_{cl(output)} = \frac{1}{2\pi(R_C + R_L)C_3}$$

Phase Shift in the Output RC Circuit The phase angle in the output *RC* circuit is

$$\theta = \tan^{-1}\left(\frac{X_{C3}}{R_C + R_L}\right)$$

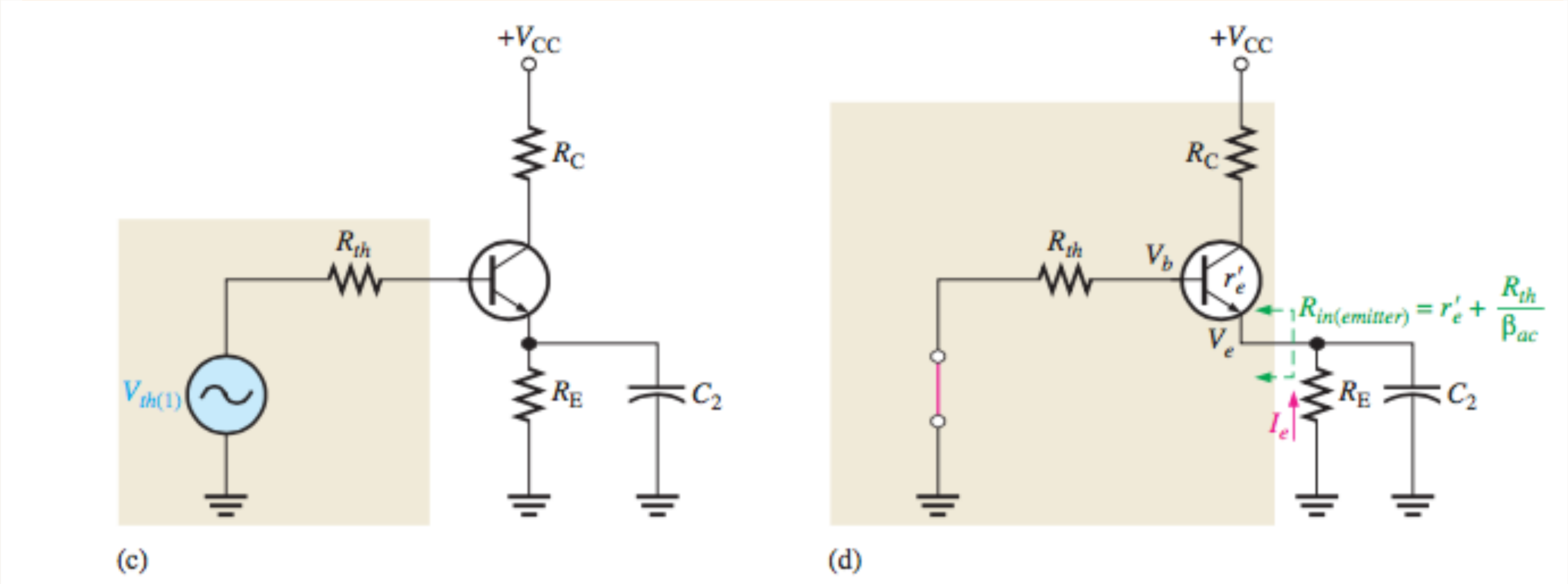
Amplifier Frequency Response

The Bypass *RC* Circuit



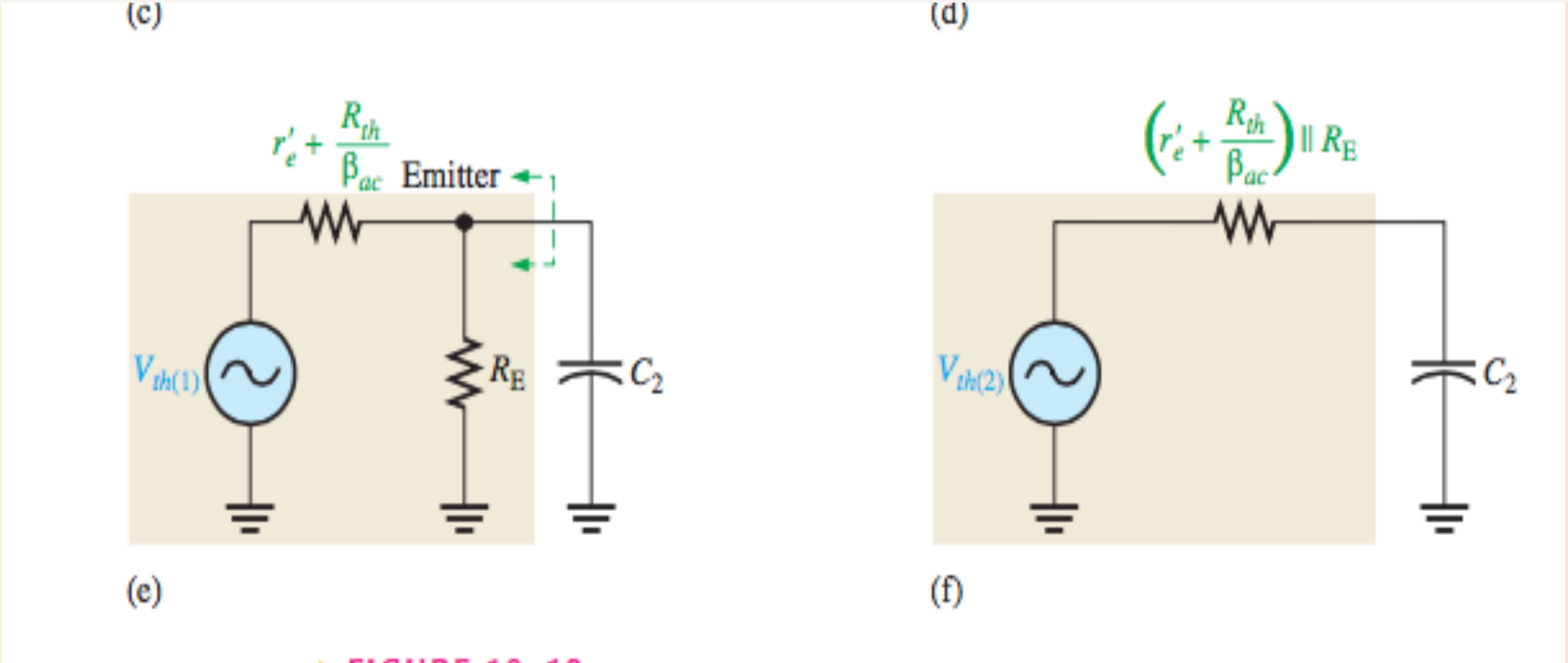
Amplifier Frequency Response

The Bypass *RC* Circuit



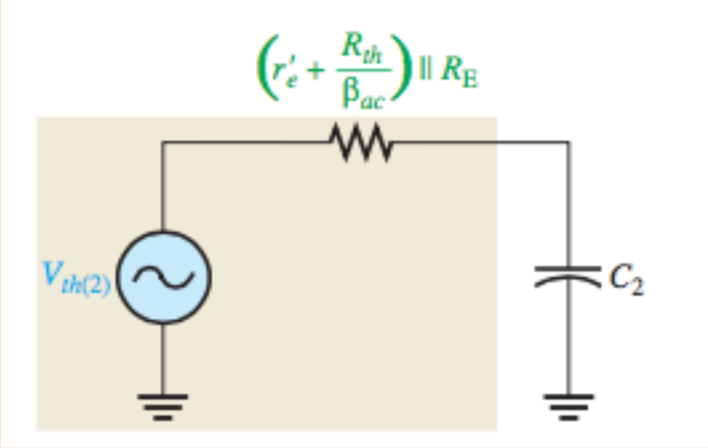
Amplifier Frequency Response

The Bypass *RC* Circuit



Amplifier Frequency Response

The Bypass *RC* Circuit



$$R_{in(emitter)} = r'_e + \frac{V_e}{I_e} \cong r'_e + \frac{V_b}{\beta_{ac} I_b} = r'_e + \frac{I_b R_{th}}{\beta_{ac} I_b}$$

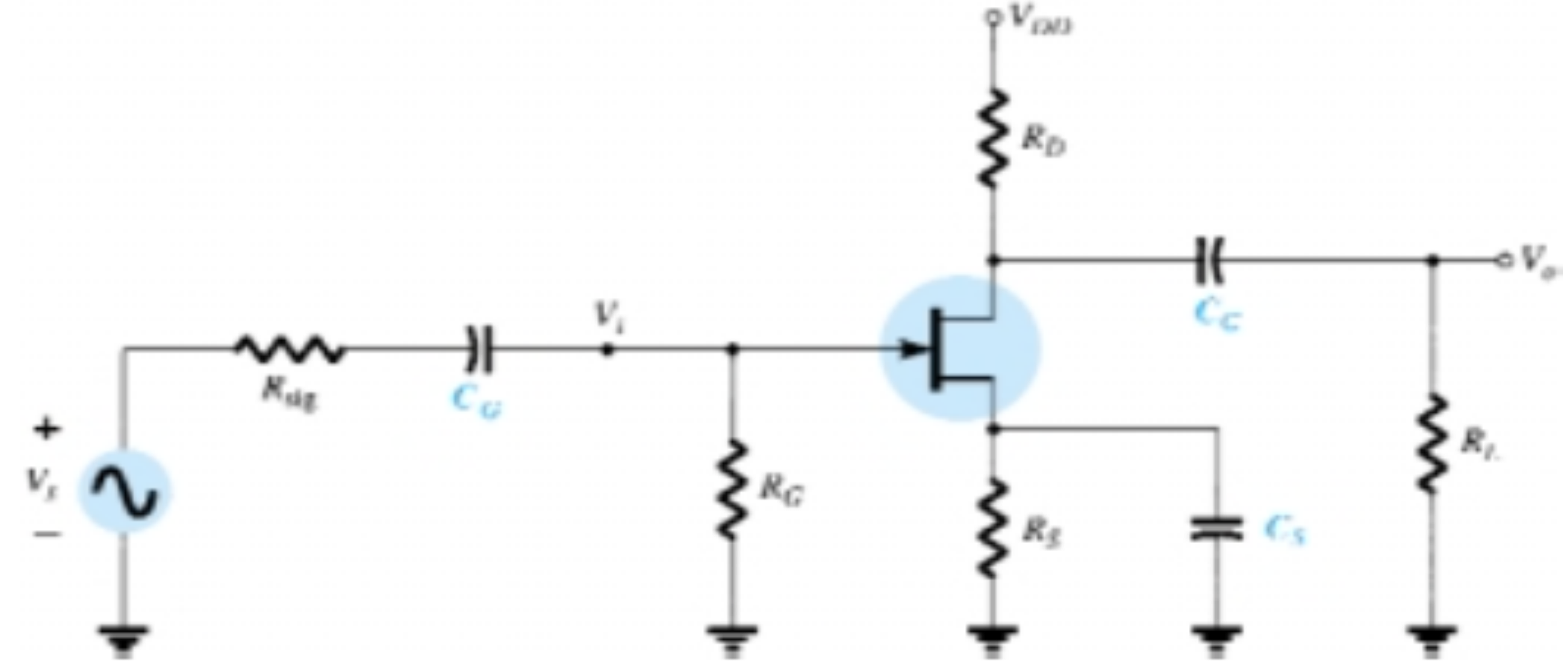
$$R_{in(emitter)} = r'_e + \frac{R_{th}}{\beta_{ac}}$$

$$f_{cl(bypass)} = \frac{1}{2\pi[(r'_e + R_{th}/\beta_{ac}) \parallel R_E]C_2}$$

$$R_{in(emitter)} = r'_e + R_{E1} + \frac{R_{th}}{\beta_{ac}}$$

Amplifier Frequency Response

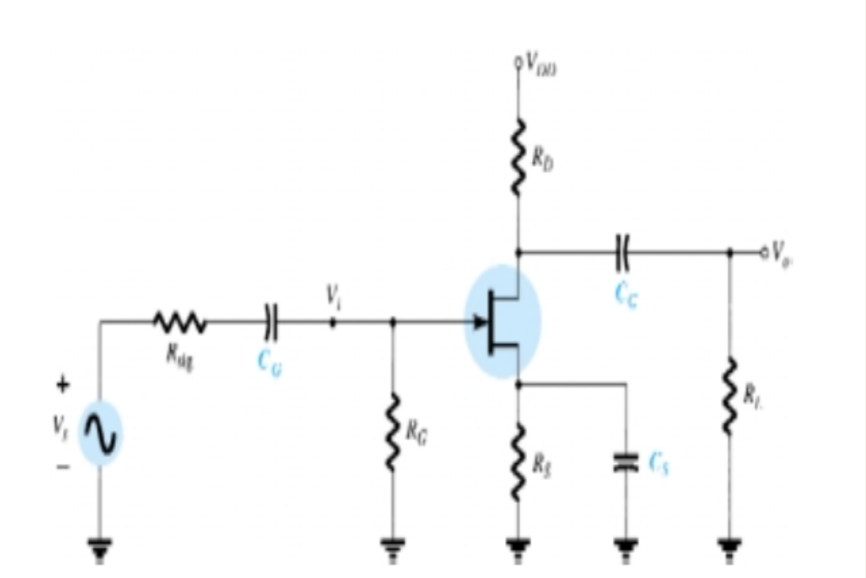
Low Frequency Response of FET:



Amplifier Frequency Response

Low Frequency Response of FET:

For C_G



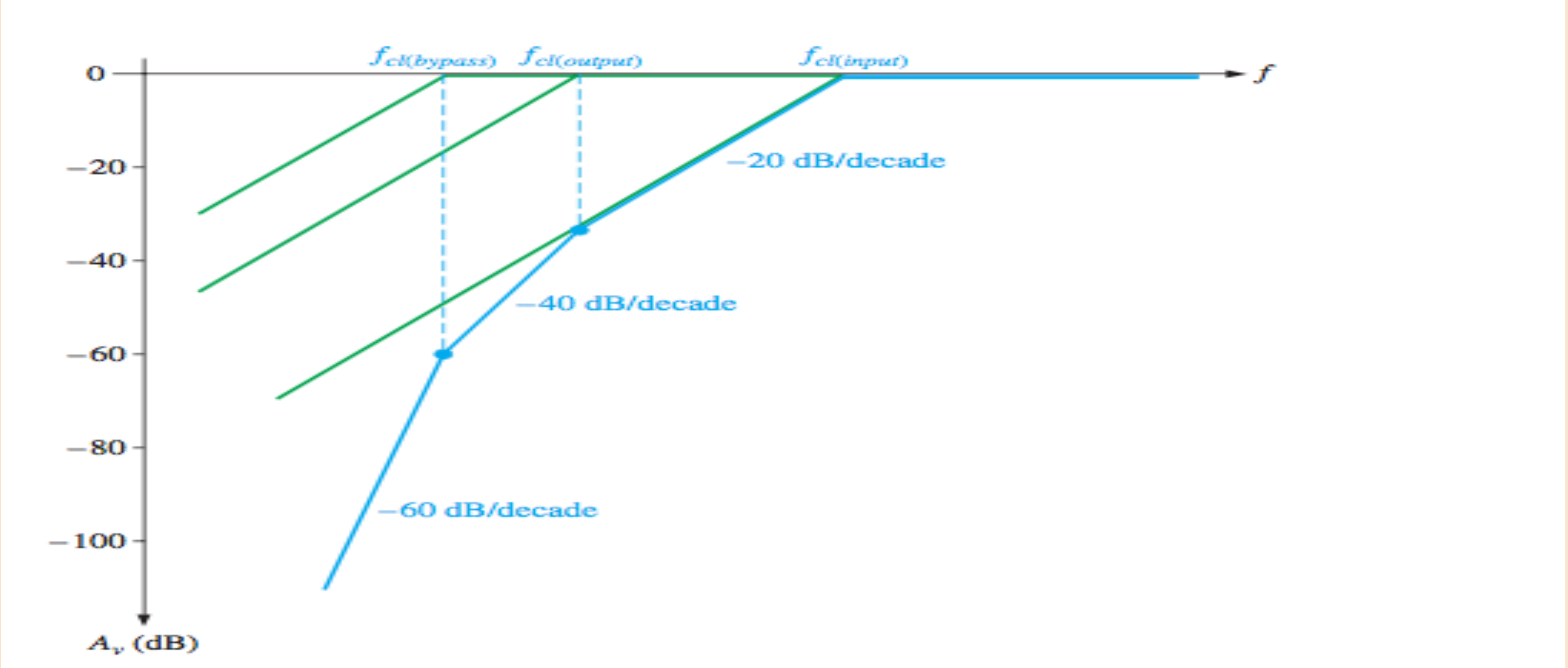
$$f_{L_G} = \frac{1}{2\pi(R_{\text{sig}} + R_i)C_G}$$

$$R_i = R_G$$

$$\theta = \tan^{-1}\left(\frac{X_{C1}}{R_{in}}\right)$$

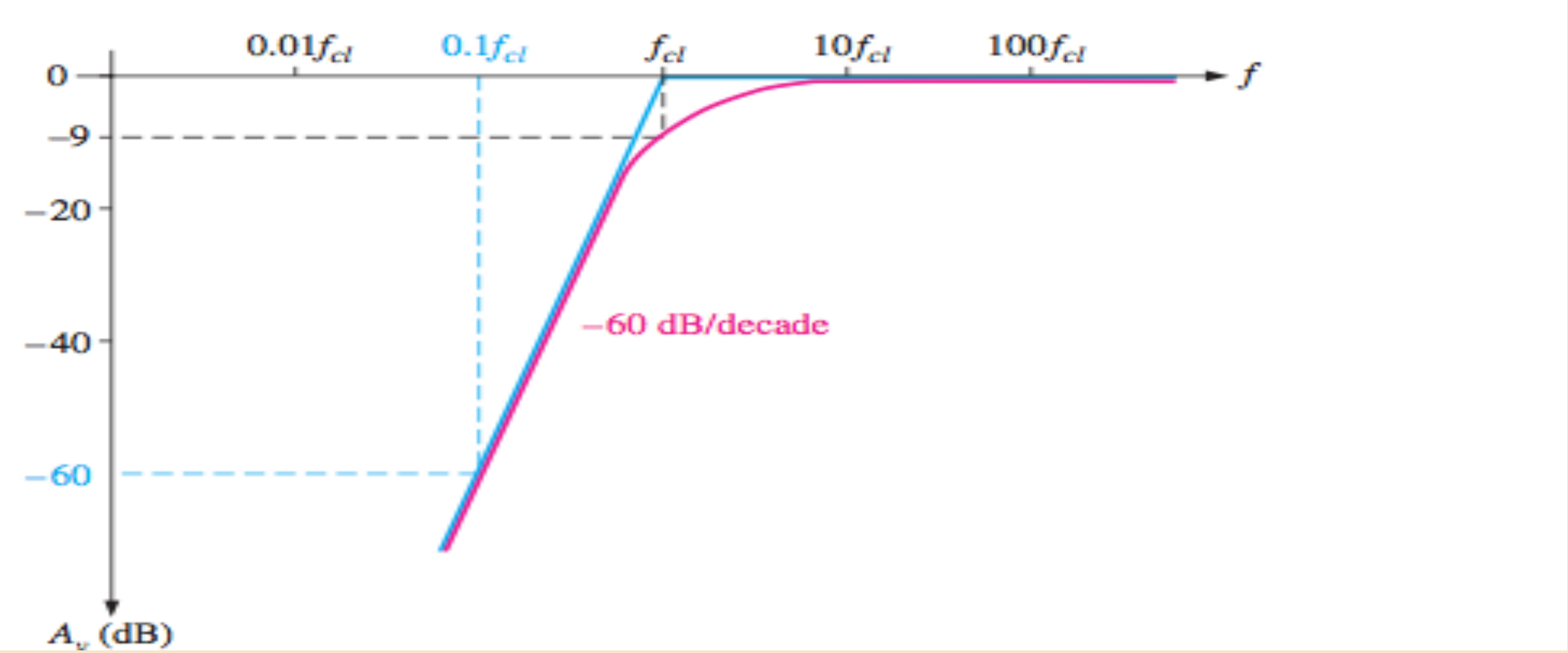
Amplifier Frequency Response

Bode plot of a BJT amplifier response for three low-frequency *RC* circuits :



Amplifier Frequency Response

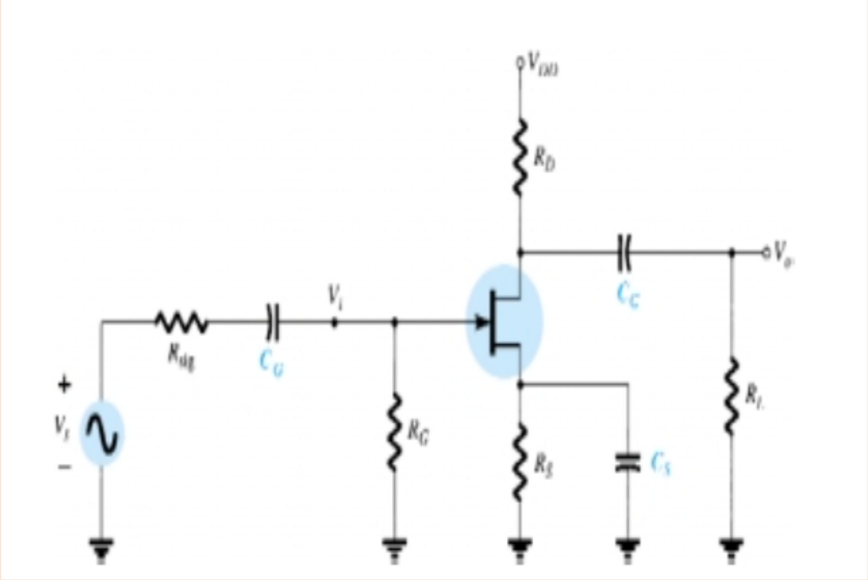
Composite Bode plot of an amplifier response where all *RC* circuits have the same *fcl*



Amplifier Frequency Response

Low Frequency Response of FET:

For C_c



$$f_{L_C} = \frac{1}{2\pi(R_o + R_L)C_C}$$

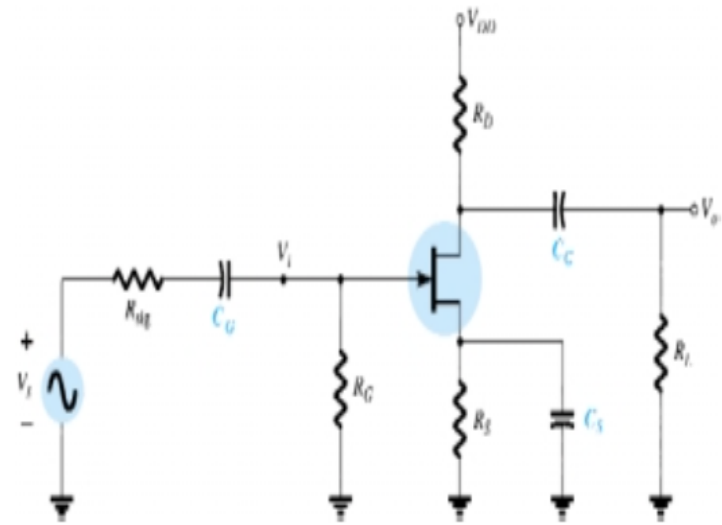
$$R_o = R_D \| r_d$$

Dr.Hossam kasem
Electronics and Electrical Comm. Dept.

Amplifier Frequency Response

Low Frequency Response of FET:

For C_S



$$\boxed{f_{L_S} = \frac{1}{2\pi R_{eq} C_S}}$$

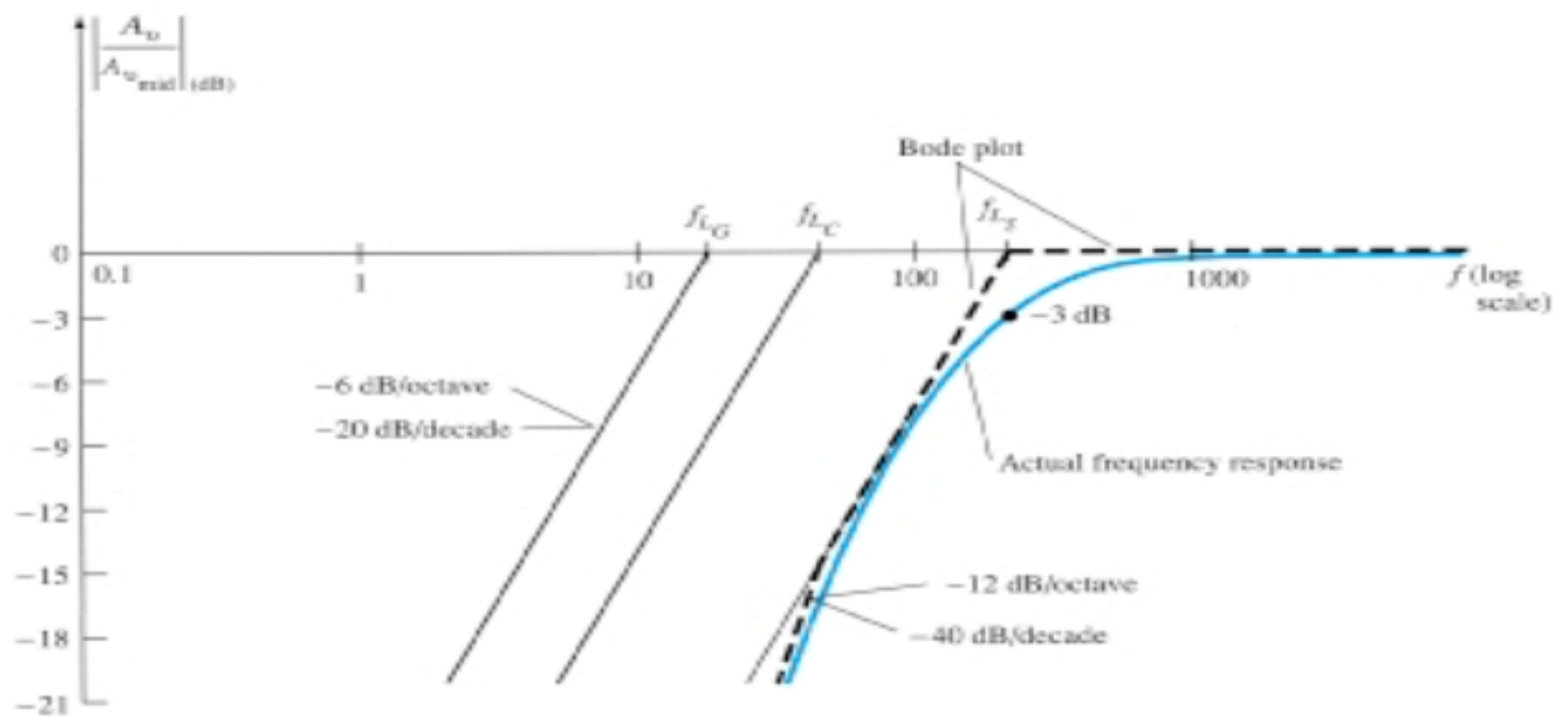
$$\boxed{R_{eq} = \frac{R_S}{1 + R_S(1 + g_m r_d)/(r_d + R_D \| R_L)}}$$

which for $r_d \cong \infty\ \Omega$ becomes

$$\boxed{R_{eq} = R_S \| \frac{1}{g_m}}$$

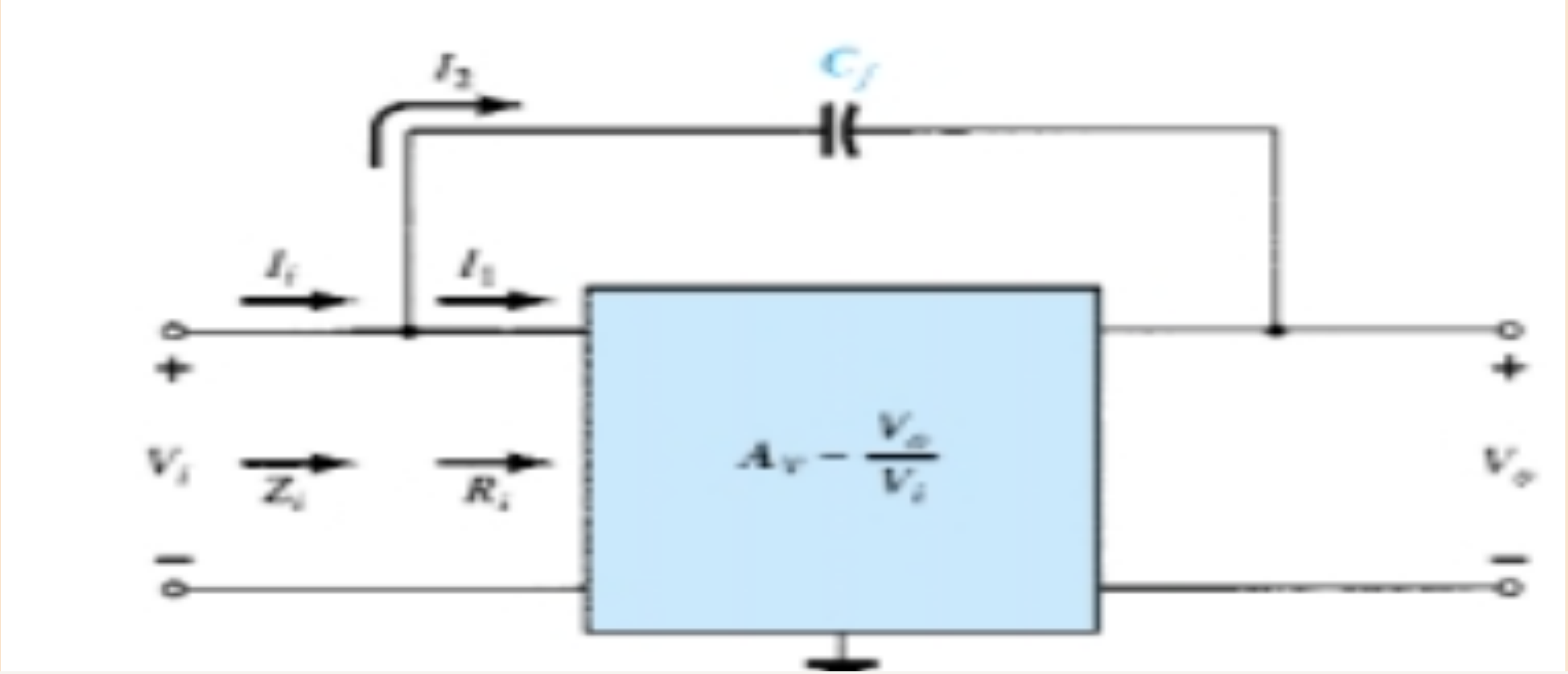
Amplifier Frequency Response

Bode plot of a FET amplifier response for three low-frequency *RC* circuits :



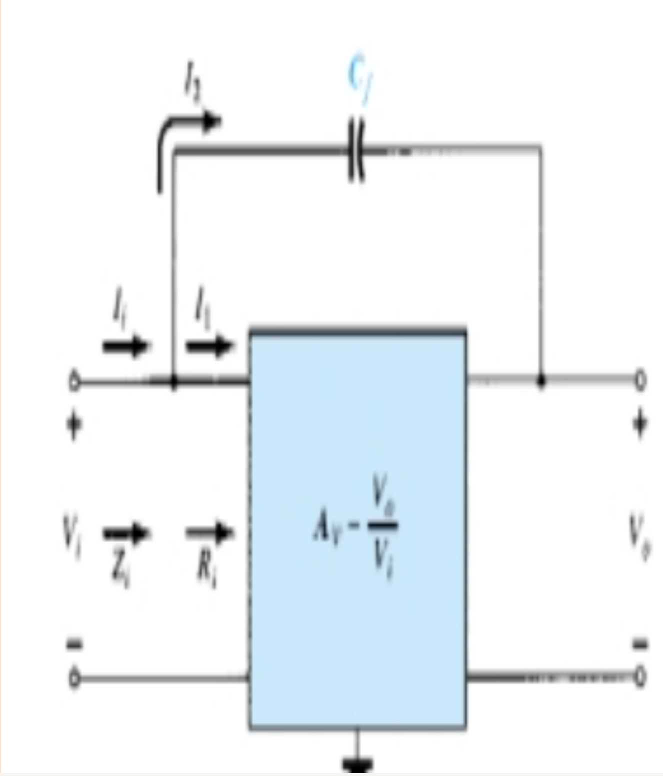
Amplifier Frequency Response

MILLER EFFECT CAPACITANCE :



Amplifier Frequency Response

MILLER EFFECT CAPACITANCE :



Applying Kirchhoff's current law gives

$$I_i = I_1 + I_2$$

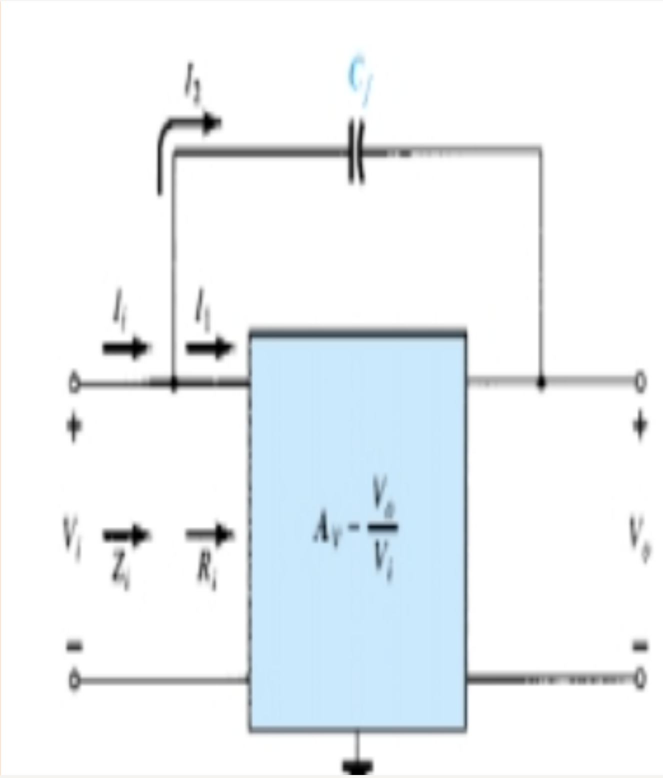
$$I_i = \frac{V_i}{Z_i}, \qquad I_1 = \frac{V_i}{R_i}$$

$$I_2 = \frac{V_i - V_o}{X_{C_f}} = \frac{V_i - A_v V_i}{X_{C_f}} = \frac{(1 - A_v)V_i}{X_{C_f}}$$

Substituting, we obtain

Amplifier Frequency Response

MILLER EFFECT CAPACITANCE :



$$\frac{V_i}{Z_i} = \frac{V_i}{R_i} + \frac{(1 - A_v)V_i}{X_{C_f}}$$

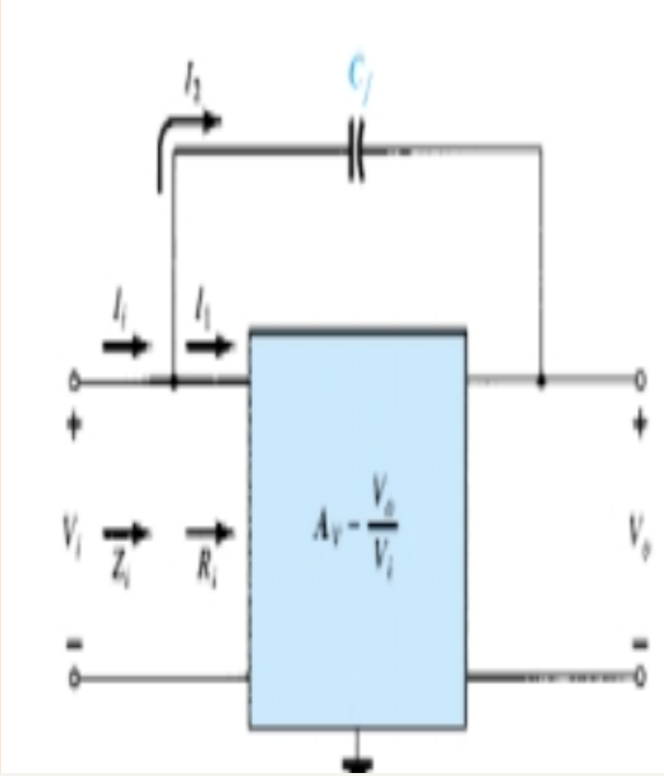
$$\frac{1}{Z_i} = \frac{1}{R_i} + \frac{1}{X_{C_f}/(1 - A_v)}$$

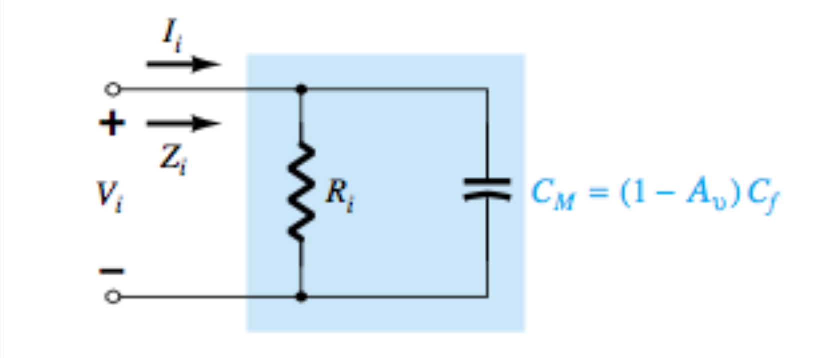
$$\frac{X_{C_f}}{1 - A_v} = \frac{1}{\underbrace{\omega\,(1 - A_v)C_f}_{C_M}} = X_{CM}$$

$$\frac{1}{Z_i} = \frac{1}{R_i} + \frac{1}{X_{C_M}}$$

Amplifier Frequency Response

MILLER EFFECT CAPACITANCE :

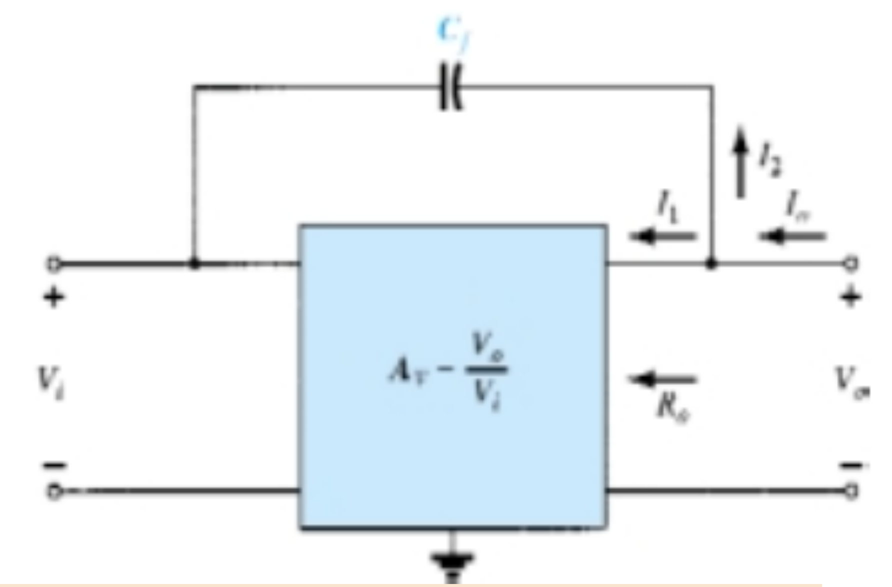




$$\boxed{C_{M_i} = (1 - A_v)C_f}$$

Amplifier Frequency Response

MILLER EFFECT CAPACITANCE :



$$I_o = I_1 + I_2$$

$$I_1 = \frac{V_o}{R_o} \quad \text{and} \quad I_2 = \frac{V_o - V_i}{X_{C_f}}$$

$$I_o \cong \frac{V_o - V_i}{X_{C_f}}$$

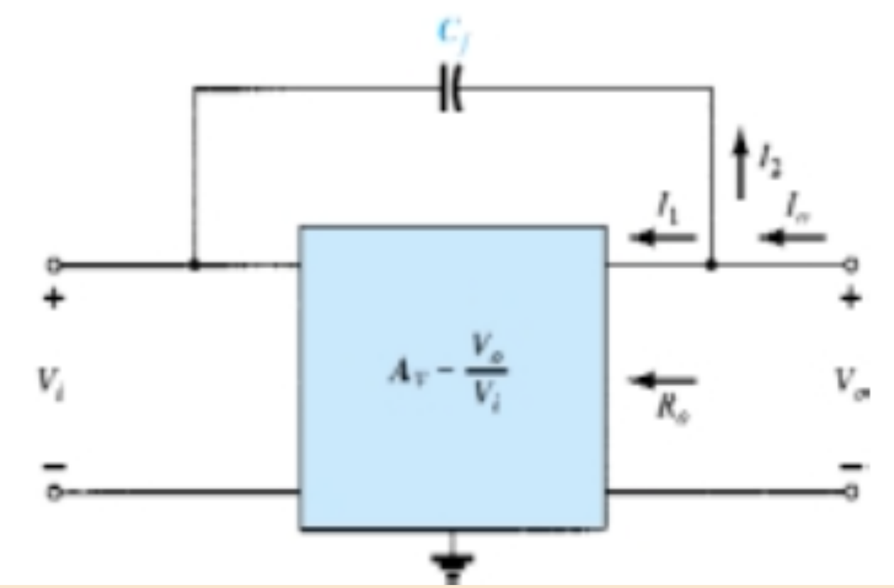
Substituting $V_i = V_o/A_v$ from $A_v = V_o/V_i$ will result in

$$I_o = \frac{V_o - V_o/A_v}{X_{C_f}} = \frac{V_o(1 - 1/A_v)}{X_{C_f}}$$

$$\frac{I_o}{V_o} = \frac{1 - 1/A_v}{X_{C_f}}$$

Amplifier Frequency Response

MILLER EFFECT CAPACITANCE :



$$\frac{V_o}{I_o} = \frac{X_{C_f}}{1 - 1/A_v} = \frac{1}{\omega C_f (1 - 1/A_v)} = \frac{1}{\omega C_{M_o}}$$

$$\boxed{C_{M_o} = \left(1 - \frac{1}{A_v}\right) C_f}$$

$$\boxed{C_{M_o} \cong C_f} \quad |A_v| \gg 1$$

Questions